WHITE PAPER DRAFT FROM THE DARK ENERGY AND COSMOLOGY PANEL
Constellation-X and Cosmology

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Over the past few years several major discoveries and advances in cosmology have occurred in both fundamental physics and astrophysics. In the area of fundamental physics, there is the discovery of dark energy and important refinements in our knowledge of the physics of dark matter. In astrophysics, there is the realization that simple models of cosmological structure formation using gravity and gas hydrodynamics do not produce a universe that looks like the in which we live. Additional physics, called feedback, is required to create the observed universe. These two "pieces" of cosmology cannot be separated. Constellation-X can make major advances in each of these areas. To fully realize the potential of Constellation-X as a tool in understanding cosmology, we will need to measure and calibrate the effects of feedback on the X-ray luminous matter in galaxy clusters and groups

I. DARK ENERGY AND DARK MATTER

In the last 5 years studies of the baryonic mass fraction in clusters of galaxies, the evolution of clusters of galaxies, type Ia supernova (SN), and the microwave background have revealed a "preposterous universe" (Carroll 2004) in which ~70% of the energy density of the Universe today is in the form of "dark energy", 26% is in the form of dark matter, and the rest is the sum of normal matter and neutrinos. In addition, the universe must be "fine tuned" such that the ratio of dark energy to dark matter today is roughly unity, despite the fact that this ratio has changed by many orders of magnitude since the big bang. More strikingly, the observed of value of the dark energy density today is many orders of magnitude smaller than the most natural values predicted by the standard model of particle physics.

These startling results have produced a revolution in cosmology and prompted the development of new cosmological models. Understanding cosmic acceleration **and** the nature of dark energy is one of the most important goals in physics and astronomy today, and it is vital that these new models be checked by a variety of precise cosmological tests over a wide range of astrophysical objects with small statistical and systematic errors. In the near term, there are several (non-X-ray) programs to study dark energy including cosmic microwave background (CMB) data, ground and HST-based SN studies, gravitational lensing studies, and studies of large scale structure. In combination, these data sets will place constraints on constant equation of state parameter dark energy models at the level of σ_w~0.1-0.15. Each of these techniques has its own limits and systematic errors. For example, one of the major systematic uncertainty of the SN-based studies is the unknown evolution of the standard candles with redshift. Other systematic concerns include the nature and subtraction of the host galaxy and the effects of gravitational lensing. Because the signal is <25% of the brightness of an individual SN at any redshift, extreme care and precision are required in the analysis and interpretation of the SN Ia data. Also the data do not lend themselves to independent checks.

Another major effort to study dark energy hinges on large-scale galaxy cluster surveys, which have a much larger signal than other techniques. For this method, the major systematic uncertainty lies in connecting the observable, such as X-ray luminosity or optical number counts, to cluster masses. These surveys allow self-calibration of the data by taking advantage of redundant cosmological information in the spatial clustering of the sources and the evolution of the mass function with redshift (observed as a luminosity function). At the core, these surveys rely on reliable and direct mass measurements, which are only possible with the high resolution, high signal-to-noise spectroscopy of Constellation-X. Constellation-X will provide more accurate and robust results from available survey data, even long after the surveys were first carried out and analyzed.

Two other longer-term projects to study dark energy, the Large Synoptic Survey Telescope (LSST) and the Joint Dark Energy Mission (JDEM), are complementary to Constellation-X. The LSST mission will focus on measuring cosmic shear and producing samples of 10^5 SN distances to z~0.8. One possible incarnation of JDEM will measure the distances to ~3000 SN to z~1.7 and will map cosmic shear over a small portion of the sky. These missions will be carried out on timescales similar to Constellation-X (LSST in 2013 and JDEM in 2014). Both claim to deliver constraints on the dark energy equation of state parameter at the level of a few percent, similar to that achievable with Constellation-X.

Constellation-X Cosmology Contributions

Constellation-X will be able to perform two independent sets of cosmological tests using X-ray measurements of clusters of galaxies. The first set of tests is measuring the absolute distances to clusters via direct and indirect means, thereby determining the transformation between redshift and true distance, d(z), which is a strong function of cosmological parameters. The second set of tests is measuring the growth of structure by using Constellation-X measurements together with theoretically informed models for how the baryon population changes with redshift to go beyond the no-evolution assumption. The number of and mass distribution of massive systems (clusters and groups of galaxies) is a very strong function of the cosmological parameters and our results will be systematics limited.

Absolute Distances

It is now clear that relaxed, simple clusters of galaxies can be used as "standard candles" (Allen et al 2004) for relative distances using the observationally-verified prediction that the fraction of the cluster mass, in rich clusters, that is in baryons is independent of redshift. X-ray observations are crucial since ~90% of all the baryons are in the hot X-ray emitting gas. The transformation from the observed X-ray temperature and surface brightness to gas mass depends on the absolute distance of the cluster, so the constant baryonic mass fraction over redshift gives strong constraints on the amount and evolution of dark energy. With its large collecting area, Constellation-X will be able to observe large samples (> 500 objects) over a wide redshift range (to z ~ 1) with high precision, which will be required to use this distance determination method. Simulations show that

Constellation-X data alone can obtain uncertainties on w to ±0.05 and, in combination with the microwave background data, constraints on w and its evolution that are

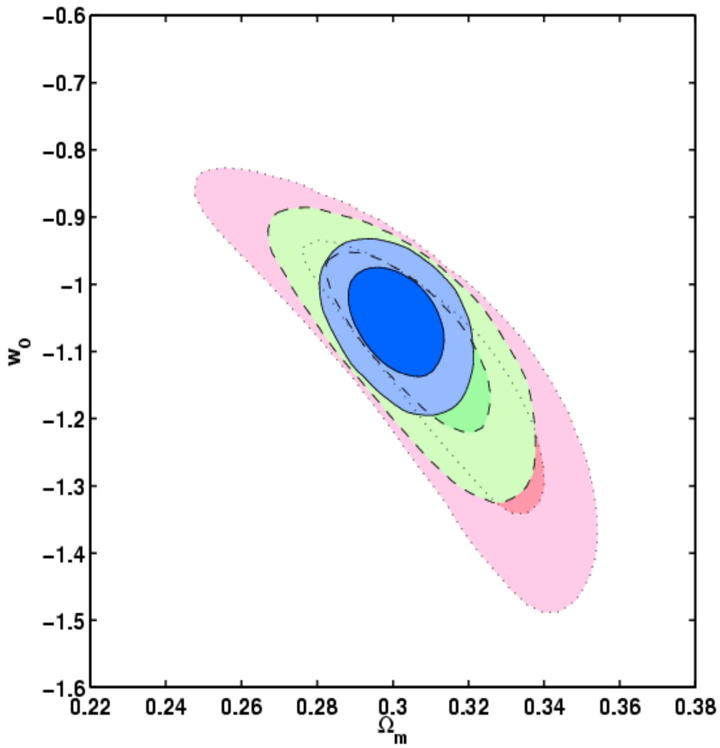

Figure 1:

substantially smaller

To utilize this technique, Constellation-X must reach scales in the cluster where gravity is dominant and have sufficient spatial resolution to recognize merging clusters and separate out the complex physics in the centers of clusters. The first requirement results in the need for a large sample of objects and a big enough field of view so that clusters can be observed out to a significant fraction of the virial radius. The large sample of objects (~500) can be done if the collecting area is sized to allow fairly fast spectral measurements. The current collecting area projected for Constellation-X can derive accurate temperature profiles for massive clusters out to z~1 in a reasonable exposure (~25 ks). The field of view is a more serious concern. The virial radius, $R_{500,}$ of massive clusters (best suited to cosmological studies) is large at all redshifts in a ΛCDM cosmology (Ettori et al 2004). For example, R_{500}~1.6' at z~1 (8 kpc/arcsec), R_{500}~3' at z~0.6 (6 kpc/arcsec), and R_{500}~5.3' at z~0.3 (4.4 kpc/arcsec). Much of the drop in size is due to "cosmological formation assumptions". The half power radius of massive clusters is >1' at all z. Thus the minimum FOV to study clusters at z > 0.3 (where Constellation-X is needed) is 6' diameter with a desirable field of view of twice this. For the second requirement, Chandra experience has raised concerns that this science can be done at 15" resolution. In order to remove point sources and select clusters without serious substructure we have a goal of 5" and a minimum requirement of better than 10".

Another method for cluster distance determination is using the Sunyaev-Zeldovich (S-Z) effect. While this method has a long history, it is only with the advent of new microwave background detectors and the XMM-Newton and Chandra observatories that the first accurate results are being obtained. Currently, the method seems to be limited by systematic errors to 15% uncertainty in distance. Constellation-X spectroscopic data and new S-Z measurements are expected to reduce this error significantly and produce precise distances. X-ray S-Z distances with a precision of ~5% would lead to measurements of cosmological parameters (Molnar et al 2004, Fox and Pen 2002) at a level of accuracy competitive with other techniques.

Another, very different technique for measuring cluster distances relies on X-ray resonance absorption against either background sources or the cluster itself compared to the cluster emission. (Krolik and Raymond 1988, Sarazin 1989, David 2000). This method relies on high-resolution spectroscopy at moderate spatial resolution, which is only possible with Constellation-X. The expected numbers of lines of sight possible with this technique (Sarazin 1989) indicate that there are over 1000 clusters whose distance can be determined by Constellation-X using background AGN, allowing a large number of further, totally independent distances to be determined. Detailed simulations of the error in distances from this technique have not yet been done.

This technique of using resonance absorption against background quasars also requires relatively high angular resolution in order for the background QSO flux to dominate the spectrum in the beam. Using Chandra data for moderate z clusters and the Sarazin 1989 calculation that a source of flux $\sim 5\times10^{-13}$ is required to achieve sufficient precision with the Con-X collecting area and a moderate exposure sets an angular resolution limit of 15". However, since this technique has not been used yet, it is not clear if this resolution is truly sufficient.

For all of the methods, there is another critical requirement for Constellation-X. This is the low background needed for precise mass profiles at large radii. In order to measure the temperature precisely, the total background should not be much more the than "residual" cosmic X-ray background in the 1-3 keV band (or ~10× less than Chandra/XMM background). While, in principle, high energy resolution is not needed to derive precise temperature and pressure profiles, we believe that calorimeter resolution is needed for a significant sample of objects to study the detailed physics of these systems (e.g. measure the additional pressure contributions from bulk motion and turbulence and derive precise temperatures) and thereby validate the use of clusters for cosmology.

CCD type resolution is adequate for baryonic mass fraction measurements, mass profiles and studying the growth of structure (physical cosmology- modulo Astro-E2 results) at the present level of accuracy. more precise measurements would benefit from better spectral resolution.

Growth of cosmic structure

Clusters of galaxies are the most massive systems in the universe and are, therefore, very sensitive probes of the rate at which cosmic structure evolves. If one can measure the mass spectrum of clusters accurately at several well-separated redshifts, one can derive the growth parameter, G(z), that is the ratio of the amplitude of fluctuations at the same mass scale as a function of cosmic time. To obtain a measurement of w as a function of z requires a relatively small sample (~100 objects) but very high precision in the mass (~4%). This test requires the precise Constellation-X mass measurements of clusters achievable only with calorimeter spectral resolution and should obtain limits on w at the level of ±0.05.

Conclusion

While several ground and space-based programs will get data before Constellation-X and claim high precision, Constellation-X is crucial to obtaining an accurate and reliable understanding of dark energy and cosmology due to the different physics, different parameter degeneracies, and different systematics. Constellation-X data will obtain the only other (besides SN Ia) direct measurements of the acceleration of the universe and will sharpen and amplify cosmological constraints from current and upcoming X-ray and S-Z cluster surveys. Constellation-X constraints on cosmological parameters will have comparable accuracy to other tests (similar to SN Ia techniques) and a tight control of systematics. In some sense the Constellation-X studies of the physics of groups and galaxy clusters will provide these extraordinary cosmological constraints for free, if we target carefully selected cluster samples (which will exist by the time of the mission).

II. THE FORMATION OF STRUCTURE IN THE UNIVERSE

The seminal work of White and Frenk (1991) showed that cold dark matter models with hydrodynamics do not reproduce observations. These models predict too many massive galaxies, the wrong evolution of galaxy masses and colors, the wrong angular momentum distribution of galaxies, the wrong spatial distribution of galaxies, the wrong entropy distribution in groups, and a host of other problems (cf. Springel 2004). As pointed out by many authors, solutions to this problem require "feedback"- the injection of momentum, energy and/or heat into the gas, which serves to counteract the effects of over-cooling.

Thus ‘feedback’ term has two currently known potential sources: star formation and active galaxies. While it seems clear that the effects of star formation will be visible as "galactic winds", heating and ionizing the IGM as well as injecting metals, the effects of AGN energy injection are not so theoretically clear. However, almost all theoretical calculations seem to indicate that the energy from young stars and SN is not sufficient to provide the observed amount of "feedback". **As opposed to the multitude of techniques used to derive cosmological parameters, only X-ray astronomy can obtain the *data* needed to determine the forces that controlled the formation of clusters and galaxies**.

Constellation-X can directly observe the injection of this "extra heat" into groups to z~1 by directly measuring the entropy of the gas as well as its dynamical state. Constellation-X can measure the energy injection in galactic winds from star forming galaxies and the metals that are being injected into the IGM at z < 2. Following up on the revolutionary Chandra and XMM results on AGN numbers and evolution, Constellation-X observations will be able to directly measure the energy put out by AGN winds, quantifying the momentum and energy in the winds using high-resolution X-ray spectra of AGN. Finally

Constellation-X will be able to directly observe the (predicted) X-ray emission from massive galaxies forming at $z < 3$, providing a direct test of the fundamental assumption of all structure formation theories that galaxies form from the cooling of shock heated virialized gas in dark matter potential wells.

A crucial constraint on the formation of structure is the determination of where and when the metals were created. While the latest optical and X-ray data on massive clusters indicate that most of the massive galaxies were in place and already old at $z \sim 1$, and that the Fe abundance at $z \sim 1$ is similar to that at lower redshifts (Tozzi et al 2003), we have no direct knowledge of the oxygen abundance, which is crucial to determining the type II SN contribution to the metallicity. We also have no knowledge of how the abundance in groups, the average place in the universe, evolves. Only Constellation-X can give us this information.

Thus Constellation-X has the potential to directly test all present day models of structure formation in the universe and provide crucial data not obtainable in any other way. **The implications of this are so broad that they are also covered in the panel reports on the high redshift universe and the black hole panel.**

In order to measure the spatially dependent gas turbulence and velocity structure necessary to constrain the amount and nature of the 'feedback' in groups Constellation-X will need a spectral resolution adequate to measure velocities of 300 km/sec (corresponding to the ~1 keV/particle "extra" energy needed in the models) with sufficient spatial resolution to map the velocity field at $z \sim 0.5$. This is equivalent to 2 eV resolution at Oxygen He-like for a $z \sim 0.5$ object with $kT \sim 1$ keV. The angular resolution requirements are not yet clear, because the requisite theoretical modeling has not been done, but this work would undoubtedly benefit from the improved spatial resolution required for the cosmology work. Sufficient throughput is needed to obtain good quality spectra in relatively short exposure times.

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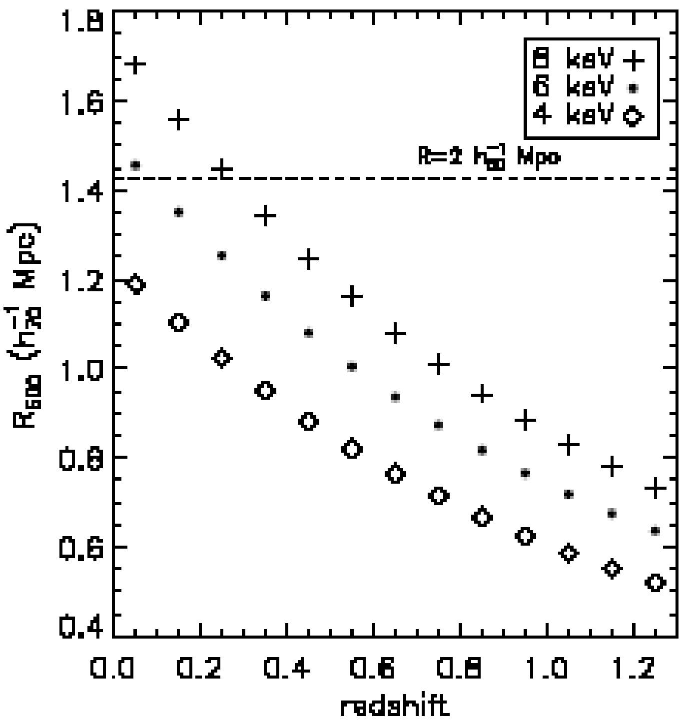

8 keV
6 keV
4 keV
R=2 h_{50}^{-1} Mpc
R_{500} (h_{70}^{-1} Mpc)
redshift